N87-11195

INTRODUCTION TO LIFE MODELING OF THERMAL BARRIER COATINGS

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INTRODUCTION

Thermal barrier coatings may be applied to air-cooled turbine section air foils to insulate such components from hot gases in the engine. The coatings, which typically consist of about 0.01 to 0.04 cm of zirconia-yttria ceramic over about 0.01 cm of NiCrAlY or NiCrAlZr alloy bond coat, allow increased gas temperatures or reduced cooling air flows. This, in turn, leads to marked improvements in engine efficiency and performance. However, certain risks are associated with designing for maximum benefits, and eventually a point is reached where coating loss would immediately jeopardize the underlying component. Therefore, designers must be able to accurately predict the life of a given bill-of-material coating in any particular design.

This paper will outline the results to date of an in-house aeronautics, base R&T program which is designed to provide the first step towards developing mission-capable life-prediction models. This work directly effects several HOST-supported contractual efforts.

FAILURE MECHANISMS AND MODEL DEVELOPMENT

Coating failure has been correlated with thermal expansion mismatch strains encountered on cooling plus additional strains arising from bond-coat oxidation (ref. 1). Figure 1(a) shows, in cross section, a thermal barrier coating system which has failed on the first cooldown after having been heated in air for 20 hr at 1250 °C. The failure morphology is typical in that a delamination crack has formed in the ceramic just above the irregular interface with the bond coat. Also, oxide layers have grown both at the interface and internally at the splat boundaries of the air-plasma-sprayed bond coat. Figure 1(b) shows that, if a duplicate specimen is heated for the same time and temperature in a shop-argon environment, little oxidation occurs and failure is not observed. This and other work (see ref. 1) demonstrates that bond-coat oxidation plays a major role in coating failure.

Figure 2 shows a specimen which is identical in composition to the coating systems in figure 1, but differs because the bond coat has been plasma sprayed at low pressure. Splat boundary oxidation has been eliminated in this specimen. However, the failure morphology of this specimen, which has been exposed to twenty-two 20-hr cycles in air at 1100 °C in a furnace is still essentially the same as that in figures 1(a) and 1(b). The cycling has led to additional, vertical cracking of the ceramic which extends from the delaminated region to the surface. When a specimen is exposed in a burner rig, failure again initiates by delamination, but subsequent cycling leads to spalling of the delaminated region (ref. 1). In either event failure initiates in the same manner (i.e., delamination on cooling) whether a specimen is tested in a furnace or a burner rig and whether the bond coat has been prepared at low pressure or atmospheric pressure.

A simple model was proposed to account for thermal barrier coating failure. First, bond-coat oxidation was assumed to be the only important time-at-temperature effect. Next, cyclic strains were assumed to promote slow crack growth in the ceramic. These strains are assumed to arise from thermal expansion mismatch between the metallic and ceramic layers and from additional strains associated with oxidation. These oxidative strains may arise when oxygen from the atmosphere is inserted into the bond coat as oxide scale, or they may be related to oxidation-induced changes in the mechanical properties of the bond coat.

A crack in the ceramic was assumed to grow according to a growth law of the type

$$\frac{da}{dN} = A\,\varepsilon^b a^d \tag{1}$$

where da/dN is the crack growth rate, ε_e is an effective strain, and a is the crack length. The expression for the effective strain caused by the combined effects of thermal expansion mismatch and oxidation was taken to be

$$\varepsilon_e = (\varepsilon_f - \varepsilon_r)(w/w_c)^m + \varepsilon_r \tag{2}$$

where ε_r represents the mismatch strain (which for convenience is discussed only in terms of the radial component), ε_f is that strain which would fail an unoxidized specimen in a single cycle, w is the oxidative weight gain, and w_c is that weight gain which would cause failure in a single cycle. Expression (2) is plotted schematically in figure 3 for three values of m; note that if effective strain is directly proportional to weight gain then m is unity. Inserting expression (2) into (1) and then rearranging and integrating gives

$$\int_0^{N_f} \left[(\varepsilon_f - \varepsilon_r)(w_N/w_c)^m + \varepsilon_r\right]^b dN = 1/a \int_{a_i}^{a_c} a^{-d}\, da \tag{3}$$

where N_f is cycles to failure, a_i is an initial crack length, and a_c is critical crack length. The subscript N has been affixed to the weight gain term to emphasize that the weight at the end of each cycle is being taken as the important life-controlling factor. This weight gain is a function of time at temperature t which is given by

$$t = N\tau \tag{4}$$

where τ is the length of each heating cycle. The weight gain is also a strong function of temperature.

The initial and critical crack lengths a_i and a_c, which serve as the integration limits to expression (3), are difficult to obtain. However, it is not necessary to evaluate these terms if one recognizes that expression (3) may be set to a constant which may be evaluated at $N_f = 1$ and $w_1 = w_c$; the constant is equal to e_f^b. Also, the integration may be replaced by a summation and, after rearranging, the final expressions for coating life is

$$\sum_{N=1}^{N_f} \left[(1 - \varepsilon_r/\varepsilon_f)(w_N/w_c)^m + \varepsilon_r/\varepsilon_f\right]^b = 1 \tag{5}$$

MODEL VERIFICATION

Initial verification of the model is discussed in references 2 and 3. In those studies the coating system consisted of a layer of air plasma sprayed ZrO_2 - 8 percent Y_2O_3 ceramic over either air-plasma-sprayed NiCrAlY or NiCrAlZr or a low-pressure plasma-sprayed NiCrAlZr. All of the coated specimens were furnace tested at about 1100 °C for cycle lengths of 1, 6, or 20 hr. The number of cycles to failure for the low-pressure plasma-sprayed NiCrAlZr system (labeled batch LZ1 in ref. 2) is plotted as functions of cycle length in figure 4. Experimental values are represented by the open symbols and modeled values by the solid symbols. These points were calculated from expression (5) using the experimental values of w_N, which were first fit to arbitrary functions, and the following parameters:

$$b = 17.00 \qquad m = 1.00$$

$$\varepsilon_r/\varepsilon_f = 0.38 \qquad w_c = 2.4 \text{ mg/cm}^2$$

It should also be emphasized that the model parameters appear to be mathematically correlated with each other, so that no one set of four parameters can be obtained from the data. Details of the experiment and the calculation are given in reference 3. As shown in figure 3 an increase in the heating cycle length from 1 to 20 hr caused the number of cycles to failure to decrease by over one order of magnitude. The model accounted for these changes quite well.

CONCLUDING REMARKS

The model discussed above represents the first step in the development of a mission-capable model for predicting the lives of thermal barrier coatings applied to turbine airfoils. Although the model has been based on simple assumptions, the results to date have been encouraging. Much more work will be required to further verify the validity of this approach, to extend it to engine operation, or to develop alternate approaches. Two important factors which must be investigated are the effect of changes in the test temperature and the effect of complex cycles. It will also be necessary to determine whether the model remains valid for specimens exposed to high heat fluxes which are typical of those encountered in gas turbine engines.

REFERENCES

1. Miller, Robert, A.; and Lowell, Carl, E.: Failure Mechanisms of Thermal Barrier Coatings Exposed to Elevated Temperatures. Thin Solid Films, vol. 95, 1982, pp. 265-273.

2. Miller, Robert A.: Oxidation Based Model for Thermal Barrier Coating Life. J. Am. Ceram. Soc., vol. 67, 1984, pp. 517-521.

3. Miller, Robert A.; Agarwal, P.; and Duderstadt, E. C.: Life Modelling of Atmospheric and Low Pressure Plasma Sprayed Thermal Barrier Coatings. Ceram. Eng. Sci. Proc.

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TBC'S FAIL IN OXIDIZING ENVIRONMENT

$ZrO_2 - Y_2O_3$/NiCrAlZr; TUBE FURNACE; 20 hr CYCLES AT 1250 °C

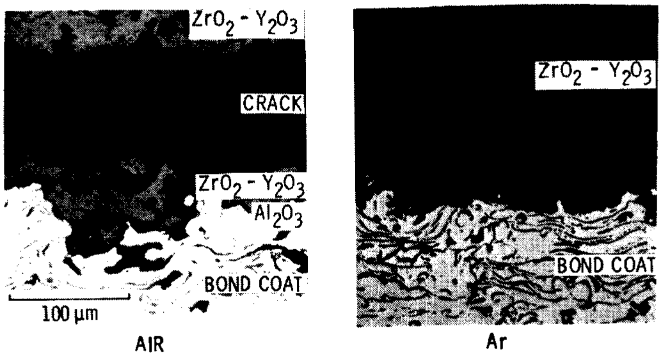

Figure 1

TBC FAILURE IN FURNACE TEST

$ZrO_2 - 8Y_2O_3$ (NASA, APPS)/
NiCrAlZr (GE, LPPS)/ B1900; 22 20-hr
CYCLES BETWEEN 1100 AND 25 °C

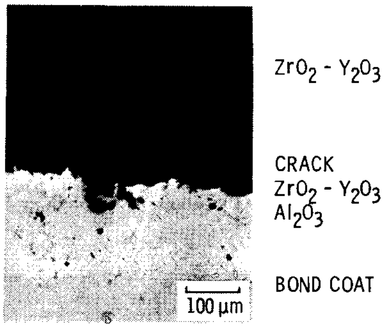

Figure 2

RELATIONSHIP FOR EFFECTIVE STRAIN

$\varepsilon_e = (\varepsilon_f - \varepsilon_r)(w/w_c)^m + \varepsilon_r$

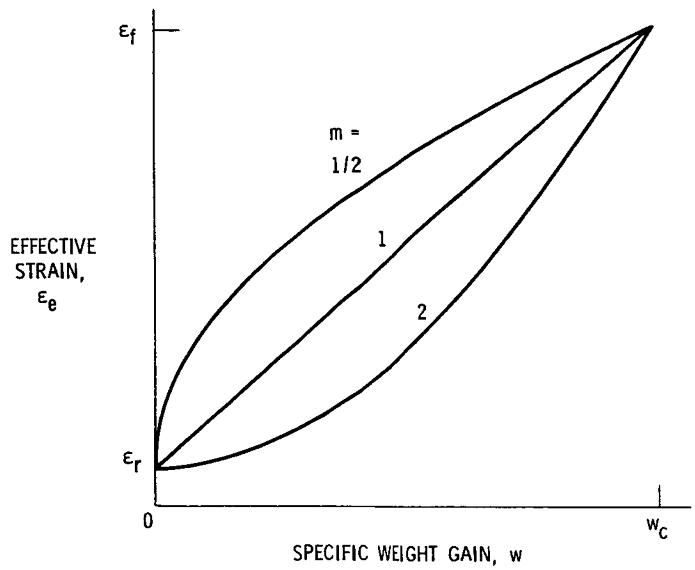

Figure 3

MEASURED AND MODELED TBC LIVES

$ZrO_2 - 8Y_2O_3$ (NASA, APPS, BATCH 1)/NiCrAlZr (GE, LPPS)/B1900; 1100 °C CYCLIC FURNACE

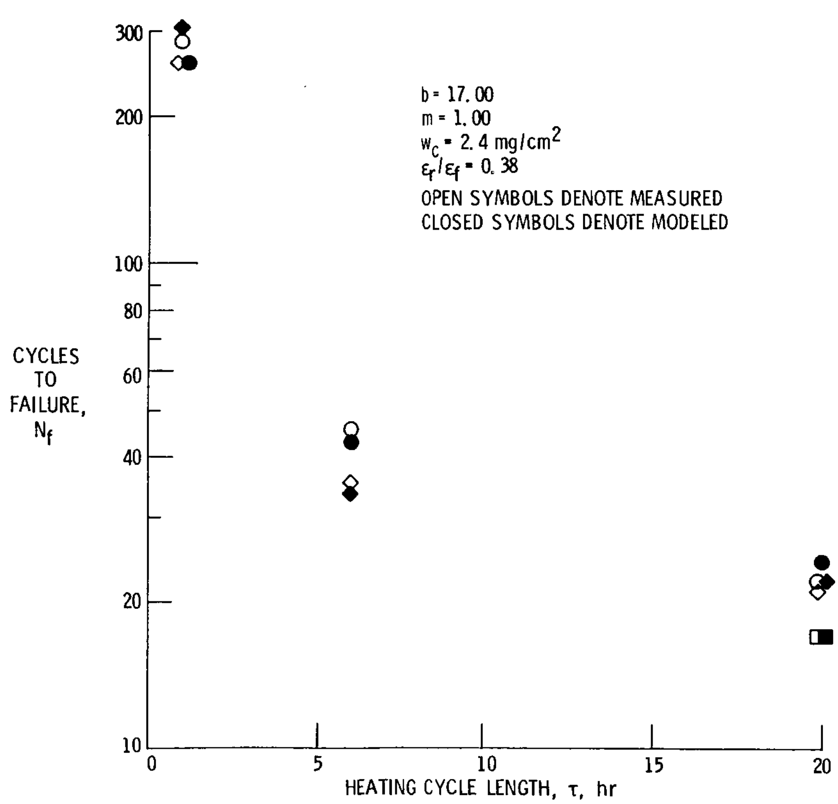

Figure 4